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**An Overview of Controls Research
on the NASA LaRC Grid**

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Interaction of Flexible Structures
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OVERVIEW

The NASA Langley Research Center has assembled a flexible grid on which control systems research can be accomplished on a two-dimensional structure that has many physically distributed sensors and actuators. The grid is a rectangular planar structure that is suspended by two cables attached to one edge so that out of plane vibrations are normal to gravity. There are six torque wheel actuators mounted to it so that torque is produced in the grid plane. Also, there are six rate gyros mounted to sense angular motion in the grid plane and eight accelerometers that measure linear acceleration normal to the grid plane. All components can be relocated to meet specific control system test requirements. Digital, analog, and hybrid control systems capability is provided in the apparatus.

To date, research on this grid has been conducted in the areas of system and parameter identification, modal estimation, distributed modal control, heirarchical adaptive control, and advanced redundancy management algorithms. The presentation overviews each technique and will present the most significant results generated for each area.

AN OVERVIEW OF CONTROLS RESEARCH ON THE NASA LaRC GRID

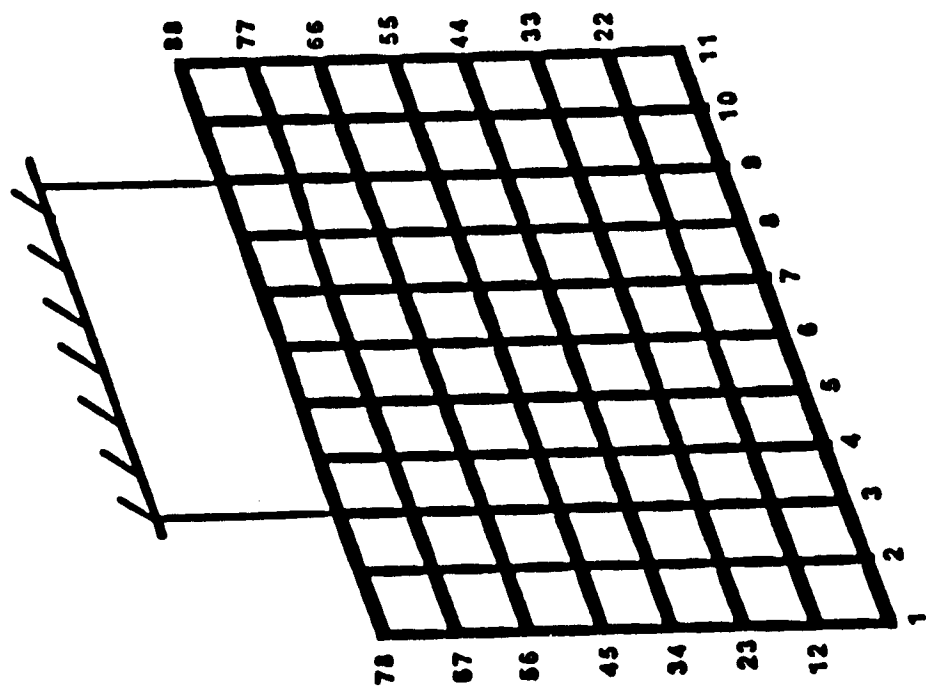
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GRID SIMULATOR MODEL

A simulator is available for interested researchers to use in the development of algorithms to be tested on the grid. Finite element modelling is used to generate mode shapes and frequencies for use in the simulator and in control system design models. The grid is modelled with 88 node points and the cable support with 8. Only out of plane motion is considered.

GRID SIMULATOR MODEL



ARCHITECTURE OF THE GRID SIMULATOR

The finite element analysis is carried out with a software package called SPAR which is available on the LaRC mainframe computer complex. This package generates printed and graphical output as well files resident on the computer complex used to transfer data efficiently to the batch simulator. The batch simulator is used both in the simulation mode and in control-system design, e.g. to calculate optimal feedback gains and filter constants for a design.

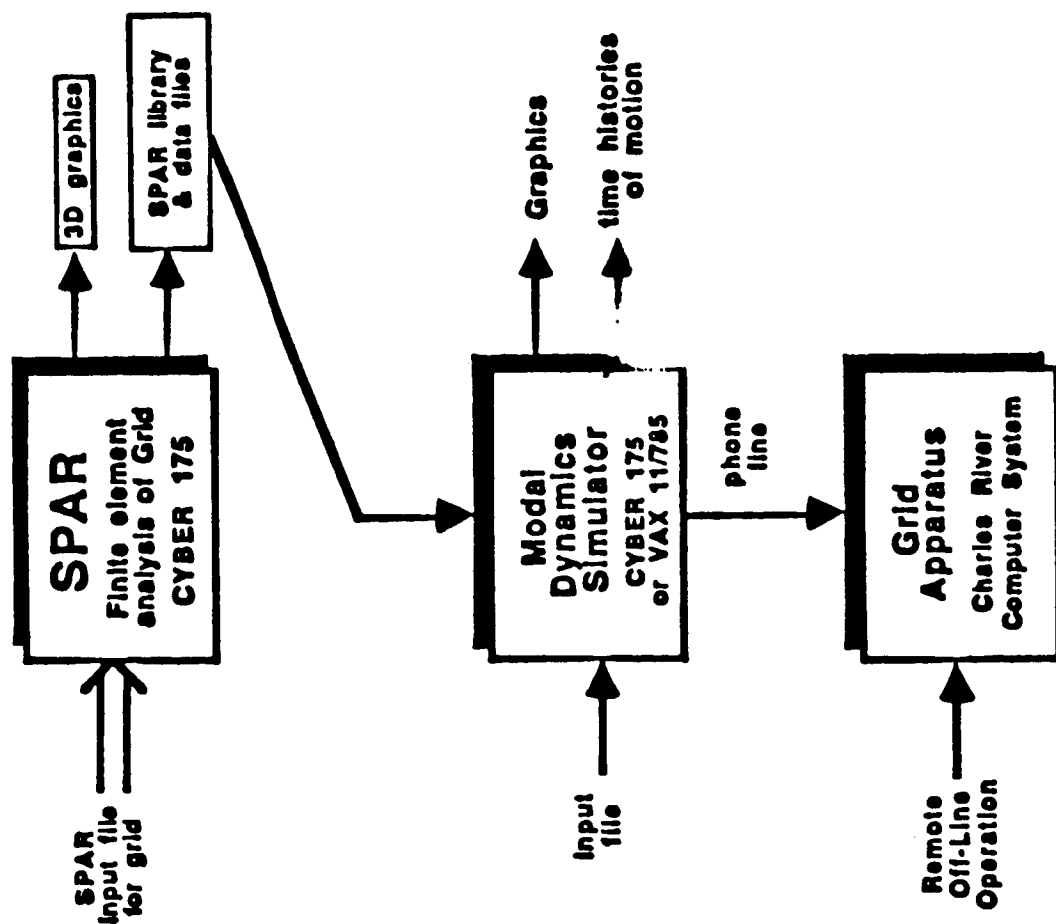
The simulator has printed and graphical output as well as output files reflecting control system design constants. These files can be transferred to the laboratory via high speed serial communication where the control law can be tested with the laboratory apparatus. The laboratory computer is a Charles River Data Computer with a UNIX lookalike operating system called UNOS.

All operations on the simulator and the laboratory apparatus can be carried out from remote sites. As an example, guest researchers at Ohio State University have successfully tested a heirarchical control law from their campus at Columbus, OH.

Some significant algorithms and results will now be described.

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ARCHITECTURE OF THE GRID SIMULATOR



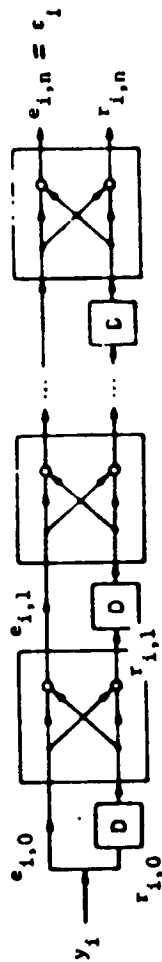
SYSTEM IDENTIFICATION USING LEAST SQUARE LATTICE FILTERS

The least square lattice filter has been used to determine mode shapes and frequencies of the grid apparatus. Records of the unforced response of the grid at several frequencies were made and frequency and damping and mode shape information was empirically determined by post-processing the records using the lattice filter. The filter is an exact, order recursive, least square solution of the linear least square estimation problem. Although the form of the filter is not linear, there is a simple method of extracting the coefficients of the linear ARMA model form from the lattice filter model. This is done by obtaining the response of the identified lattice filter to the input sequence $\{1, 0, 0, \dots, 0\}$. Deciding the proper order of the model given the input data is also required. This has been done by graphing the norm of the model error and selecting the model order as the lowest whose error norm is less than a given threshold. The application of the lattice filter to the grid is presented in:

Montgomery, R. C. and N. Sundararajan: The Application of Least Square Lattice Filters for Identifying the Dynamics of a Two-Dimensional Grid Structure. *Journal of Astronautical Sciences*, Vol. 33, No. 1, January-March 1985, pp. 35-47.

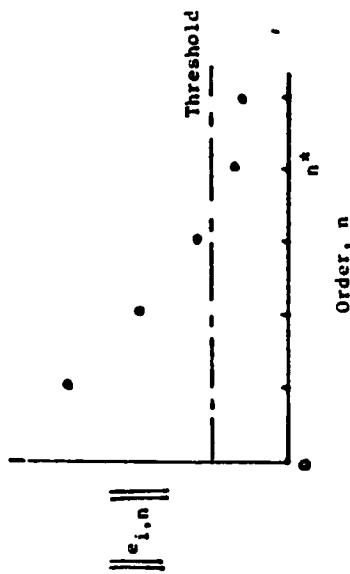
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LSL IN VARIABLE ORDER SYSTEMS ID



Structural Dynamics Models $y_k = \psi_k + \eta_k$

Order Determination

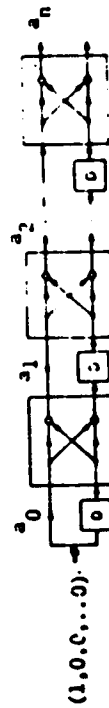


Relation to LSL $y_i = \phi_L \psi_{L_i} + e_i$

$$\phi_L = [r_{i-1,0}, \dots, r_{i-1,n-1}]$$

$$\psi_L = (k_{i,1}, \dots, k_{i,u})$$

AR Parameter Extraction



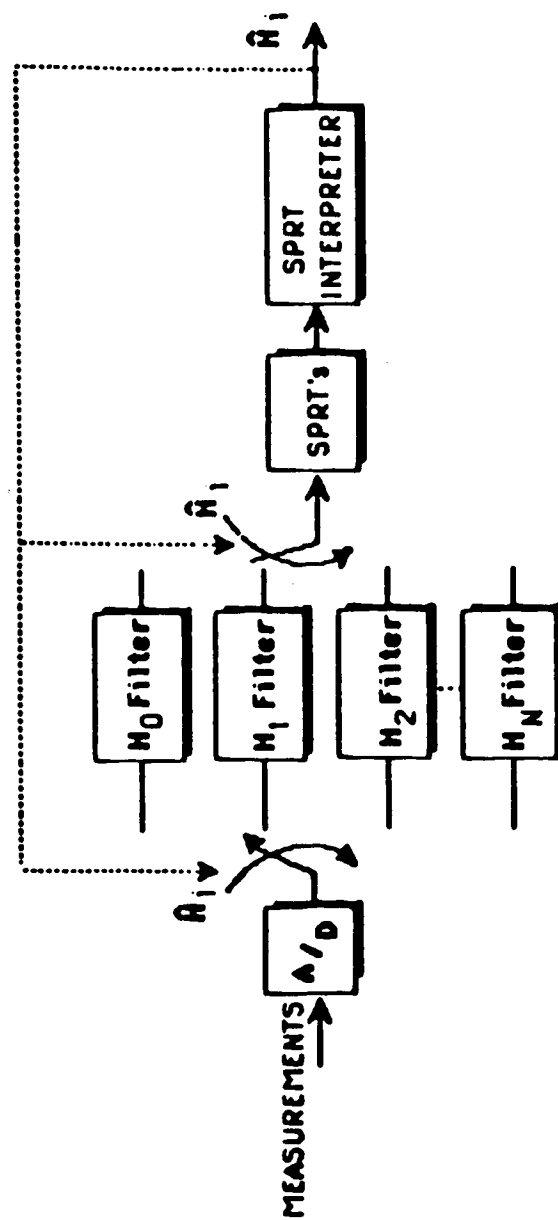
FAILURE DETECTION AND CONTROL SYSTEM RECONFIGURATION

Research on advanced failure detection and system reconfiguration methods has also been accomplished on the grid apparatus. Because of the computational limitations parallel optimal decision theory methods (e.g. banks of Kalman filters operating in parallel using different sets of input data) could not be investigated and a scheme employing sequential testing was developed. In this scheme a bank of Kalman filters is used, however, only one is on-line at a time. The decision to switch to another filter is made by examining the residuals of the operating filter using the sequential probability ratio test (SPRT). Which filter to switch to is determined by the SPRT interpreter. This research is reported in:

Williams, J. P. and R. C. Montgomery: Failure Detection and Accommodation in Structural Dynamics Systems Using Analytic Redundancy. 24th IEEE Conference on Decision and Control. Ft. Lauderdale, FL, December 11-13, 1985, pp. 906-910.

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FAILURE HYPOTHESIS TESTING



SEQUENTIAL PROBABILITY RATIO TEST (SPRT)

The sequential probability ratio test (SPRT) makes a selection of one from two possible decisions. It is an optimal binary decision test that makes the decision in the least number of observations. It is used with the innovations sequence of the active Kalman filter to decide between the two decisions: the sequence is Gaussian with zero mean and given variance or, the sequence is Gaussian with mean m and given variance. The former case corresponds to the hypothesis of no failures whereas the later corresponds to a failure being present in the system. When a failure is detected the innovation sequence is examined to isolate the failed component.

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SEQUENTIAL PROBABILITY RATIO TEST (SPRT)

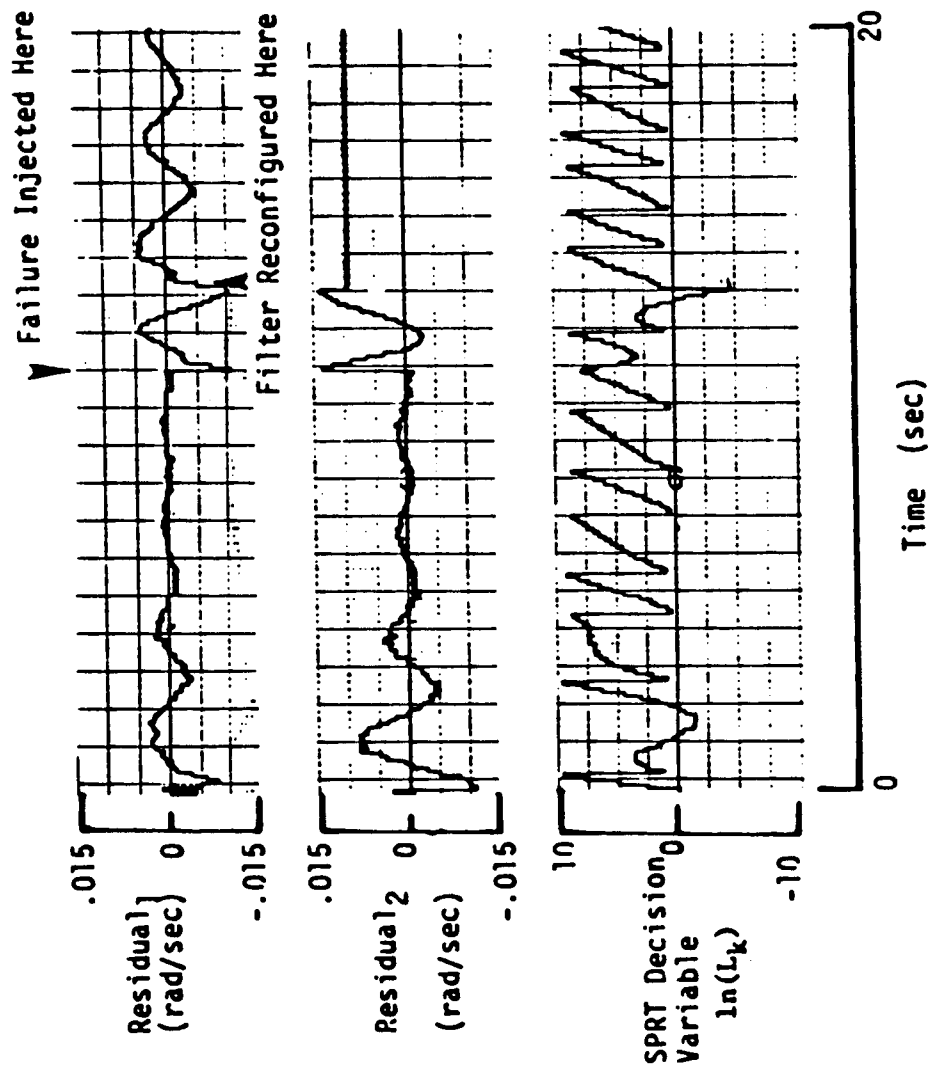
- * BINARY HYPOTHESIS TEST
- * ECONOMIZES ON THE NUMBER OF OBSERVATIONS REQUIRED TO MAKE A DECISION ON THE STATISTICS OF A SAMPLE
- * USED HERE TO DECIDE WHICH HYPOTHESIS ON THE KALMAN FILTER RESIDUAL SEQUENCE IS MOST PROBABLY TRUE:
 - H₀: K-F INNOVATIONS SEQUENCE IS GAUSSIAN WITH
MEAN 0 AND VARIANCE σ^2
(NO FAILURE HYPOTHESIS)
 - H₁: K-F INNOVATIONS SEQUENCE IS GAUSSIAN WITH
MEAN m AND VARIANCE σ^2
(FAILURE HYPOTHESIS)

FAILURE DETECTION AND RECONFIGURATION

The figure shows time histories of on-line failure detection using the SPRT algorithm to detect a failure. Depending on the input data, each time a SPRT is started the decision variable will drift from its initial value of zero towards the decision thresholds. The time required to reach and cross one of the thresholds is the decision time. This is a theoretical minimum for the SPRT algorithm. A tendency of the decision variable to drift to the failure threshold can be caused by modelling errors or other events that make the residual (or innovations sequence) non-white. In application to structural dynamics systems one obvious cause is spillover of unmodelled structural modes into the residuals. The assumption here is that the cause is a failure of a sensor or actuator. Each time a "no failure" decision is made a new SPRT is started. Following a "failure" decision the residuals are examined to determine which failure, if any, caused the alarm. After successful isolation of the failure, a new filter, designed to operate without the failed component, is used.

For the example of this histogram only sensor failures are considered. Also, the "no failure" threshold is positive and the "failure" threshold is negative. At the start of the histograms there are no failures. Note that the residuals are non-white and that they cause a delay in the decision time since the decision variable drifts toward the "failure" threshold. As time progresses the effects of initializing the Kalman filter decay and the non-white nature of the residual is smaller. The SPRT in this case makes the decision rapidly without a tendency of the decision variable to move toward the "failure" decision. In the later phase of the histogram a failure is injected into the system. It is detected and isolated and a new filter is initialized that is designed without the failed sensor. The sawtooth wave near the end of the histogram indicates successful recovery of the system from the failure.

FAILURE DETECTION AND RECONFIGURATION



DECENTRALIZED ADAPTIVE CONTROL STRUCTURE

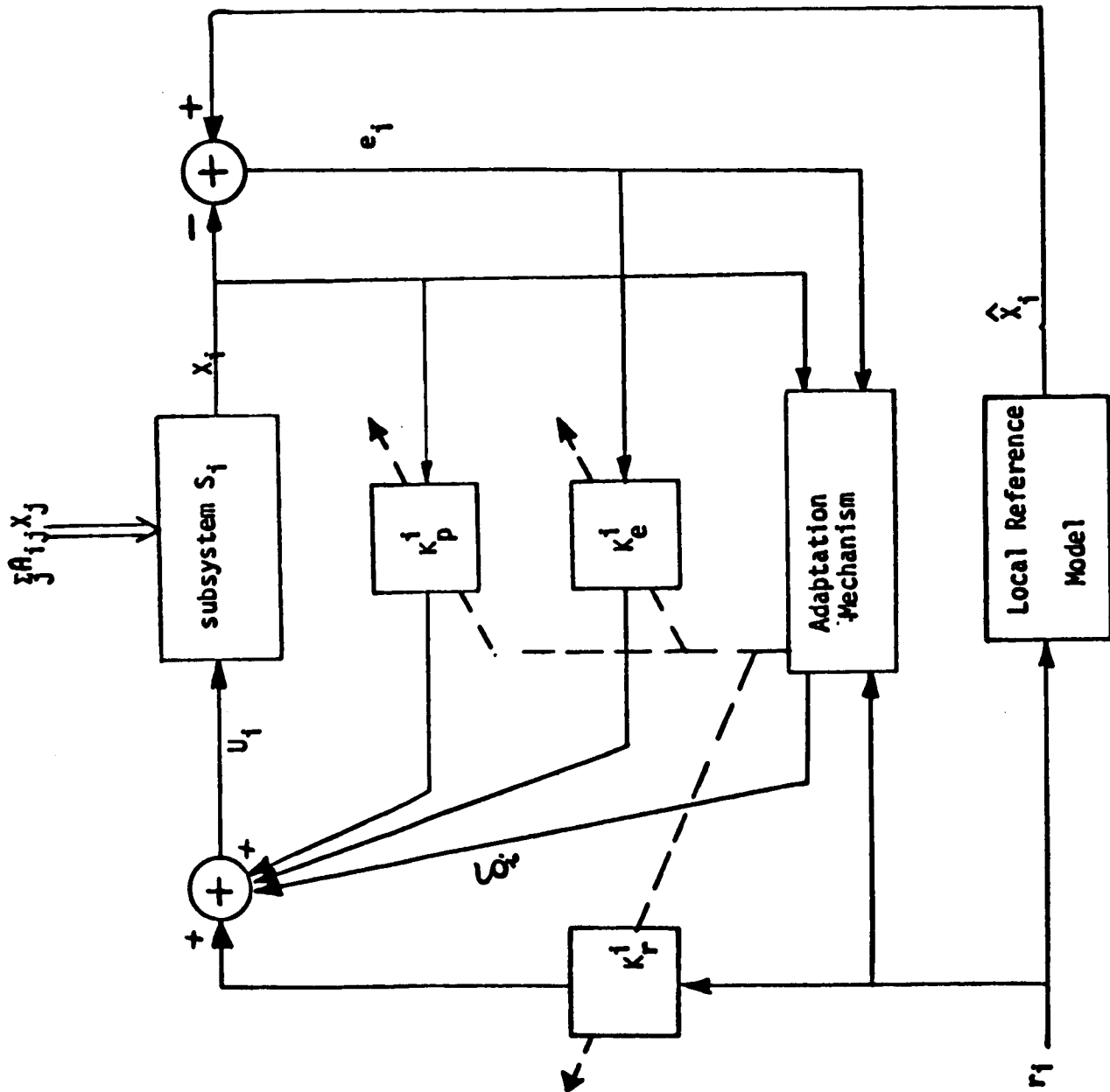
A decentralized adaptive control scheme was remotely tested on the Langley grid apparatus from the Ohio State University. The adaptive control scheme investigated considers a group of linear subsystems consisting of linear state dynamics with coupling to the other subsystems, a measurement, and an actuator. Each subsystem has a linear controller with a gain on its measured subsystem state, on the input, and on the error between the actual subsystem state and its reference state as generated by a reference model in response to the input. The gains are driven by adaptation logic that is the subject of the research.

A more complete description of this research is reported in:

Dzguner, U., Yurkovitch, S., Martin, J., III, and F. Al-Abbass:
Decentralized Control Experiments on NASA's Flexible Grid. Proceedings
of the 1986 American Control Conference, Volume II, pp. 1045-1051.
Seattle, WA. June 19, 1986.

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DECENTRALIZED ADAPTIVE CONTROL STRUCTURE

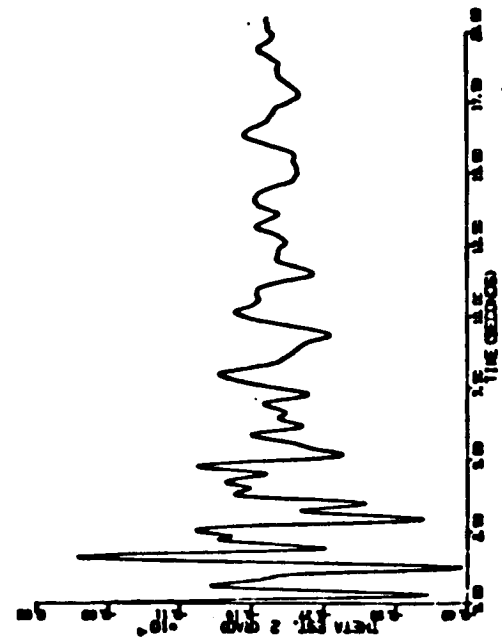
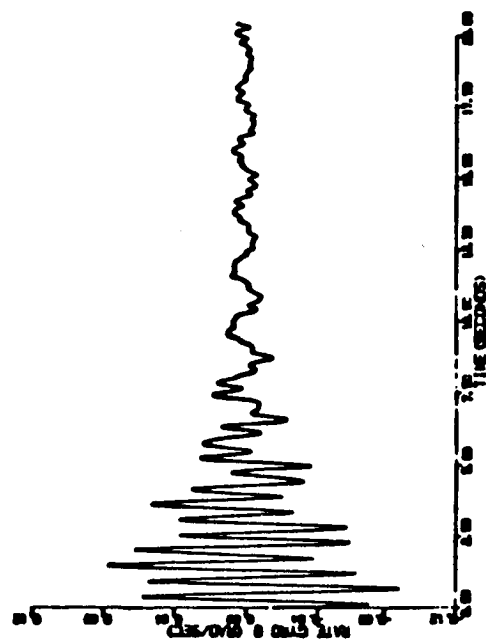


DECENTRALIZED ADAPTIVE CONTROL OF THE GRID

This chart shows simulation time histories of the rate gyro outputs and the angle estimates on the Langley grid. The controller is the decentralized adaptive controller previously described wherein each mode was considered as a separate subsystem. The controller is stable and produces damping in all simulated modes.

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DECENTRALIZED ADAPTIVE CONTROL OF THE GRID



SUMMARY

The Langley grid apparatus has been used in the conduct of research in several areas of interest in the control of large flexible spacecraft. These include system identification, modal estimation, distributed modal control, heirarchical adaptive control, and advanced redundancy management techniques. Some of these research areas have been described herein. The grid will continue to be available over the next several years providing the academic community oportunities for research that are not available at most universities. The remote testing capability of the facility allows researchers the use of realistic hardware to validate their theories from their own remote site.

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SUMMARY

- * THE GRID APPARATUS HAS BEEN USED TO CONDUCT RESEARCH IN A NUMBER OF AREAS IMPORTANT TO THE CONTROL OF LARGE FLEXIBLE SPACE STRUCTURES. SOME OF THE AREAS ARE:
 - SYSTEM AND PARAMETER IDENTIFICATION
 - MODAL ESTIMATION
 - DISTRIBUTED MODAL CONTROL
 - HIEARCHIAL ADAPTIVE CONTROL
 - ADVANCED REDUNDANCY MANAGEMENT
- * THE GRID AND THE CONTROL PROCESSING COMPUTER ARE A GOOD TEST-BED FOR THE NEW ESTIMATION, CONTROL, AND REDUNDANCEY MANAGEMENT TECHNIQUES
- * IT IS POSSIBLE TO RUN CLOSED LOOP EXPERIMENTS FROM REMOTE SITES